U.S. Department of the Interior
U.S. Geological Survey

Hydraulic-Property Estimates for Use With a Transient Ground-Water Flow Model of the Death Valley Regional Ground-Water Flow System, Nevada and California

Water-Resources Investigations Report 01-4210

Prepared in cooperation with the
OFFICE OF ENVIRONMENTAL RESTORATION AND WASTE MANAGEMENT,
U.S. DEPARTMENT OF ENERGY
National Nuclear Security Administration
Nevada Operations Office, under
Interagency Agreement DE-AI08-96NV11967

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By Wayne R. Belcher *and* Peggy E. Elliott

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CONVERSION FACTORS, VERTICAL DATUM, AND ABBREVIATIONS

Multiply	By	To obtain
cubic meter per day (m^3/d)	35.31	cubic foot per day
centimeter (cm)	0.394	inch
kilometer (km)	0.62137	mile
square kilometer (km^2)	0.3861	square mile
kilopascal (kPa)	0.14503	pound per square inch
liter (L)	0.26417	gallon
liter per second (L/s)	15.85	gallon per minute
meter (m)	3.2808	foot
meter per day (m/d)	3.2808	foot per day
meter squared per day (m^2/d)	10.76	foot squared per day
meter squared per day (m^2/d)	0.055916	gallon per minute per foot
meter squared per day (m^2/d)	80.52	gallon per day per foot
square meter (m^2)	10.76	square foot

Temperature: Degree Celsius (°C) may be converted to degree Fahrenheit (°F) by using the following equation: °F = (1.8 x °C) + 32.

Sea level: In this report, “sea level” refers to the National Geodetic Vertical Datum of 1929 (NGVD of 1929, formerly called “Sea-Level Datum of 1929”), which is derived from a general adjustment of the first-order leveling networks of the United States and Canada.

Acronyms:

ACU	Alluvial confining unit
ANCOVA	Analysis of covariance
BRU	Belted Range unit
CFVU	Crater Flat volcanic unit
CHVU	Calico Hills volcanic unit
DOD	U.S. Department of Defense
DOE	U.S. Department of Energy
DVRFS	Death Valley regional ground-water flow system
HGU	Hydrogeologic unit
HRMP	Hydrologic resources management program
ICU	Intrusive confining unit
LCA	Lower carbonate aquifer
LCCU	Lower clastic confining unit
LFU	Lava flow unit
NTS	Nevada Test Site
NWIS	National Water Information System
OAA	Older alluvial aquifer
OVU	Older volcanics unit
PVA	Paintbrush volcanic aquifer
SCU	Sedimentary confining unit
SWNVF	Southwest Nevada volcanic field
TMVA	Thirsty Canyon/Timber Mountain volcanic aquifer
TV	Tertiary volcanics
UCA	Upper carbonate aquifer
UCCU	Upper clastic confining unit
UGTA	Underground Testing Area
USGS	U.S. Geological Survey
VSU	Volcaniclastics and sediments unit
WVU	Wahmonie volcanic unit
YAA	Younger alluvial aquifer
YMP	Yucca Mountain Project
YVU	Younger volcanic unit
XCU	Crystalline confining unit

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ABSTRACT

The Death Valley regional ground-water flow system encompasses an area of about 43,500 square kilometers in southeastern California and southern Nevada, between latitudes 35° and 38°15′ north and longitudes 115° and 117°45′ west. The study area is underlain by Quaternary to Tertiary basin-fill sediments and mafic-lava flows; Tertiary volcanic, volcaniclastic, and sedimentary rocks; Tertiary to Jurassic granitic rocks; Triassic to Middle Proterozoic carbonate and clastic sedimentary rocks; and Early Proterozoic igneous and metamorphic rocks. The rock assemblage in the Death Valley region is extensively faulted as a result of several episodes of tectonic activity.

This study is comprised of published and unpublished estimates of transmissivity, hydraulic conductivity, storage coefficient, and anisotropy ratios for hydrogeologic units within the Death Valley region study area. Hydrogeologic units previously proposed for the Death Valley regional transient ground-water flow model, were recognized for the purpose of studying the distribution of hydraulic properties. Analyses of regression and covariance were used to assess if a relation existed between hydraulic conductivity and depth for most hydrogeologic units. Those analyses showed a weak, quantitatively indeterminate, relation between hydraulic conductivity and depth.

INTRODUCTION

The U.S. Department of Energy (DOE) and the U.S. Department of Defense (DOD) conducted various types of underground nuclear tests at the Nevada Test Site (NTS) in southern Nevada (fig. 1) between 1951 and 1992. Those tests produced radionuclides that contaminated ground water beneath portions of the NTS. In 1972, DOE established a long-term monitoring program to detect the presence of any radioactivity that may have been related to nuclear testing activities. Currently, DOE is evaluating contaminated areas as part of the Environmental Restoration program. The U.S. Geological Survey (USGS), in cooperation with the DOE, is evaluating the geologic and hydrologic characteristics of an area near Yucca Mountain, adjacent to the NTS, which is being considered for construction of an underground high-level nuclear waste repository. As part of these programs, the USGS is evaluating the regional ground-water flow system in the Death Valley region.

USGS evaluations include a detailed characterization of the ground-water flow system including development of a regional three-dimensional (3-D) conceptual and numerical ground-water flow model to help: (1) characterize regional 3-D ground-water flow paths, (2) define boundaries of the subregional and local flow systems, (3) define locations of regional ground-water discharges, (4) estimate magnitudes and rates of regional subsurface flux, (5) evaluate existing and potential anthropogenic effects on ground-water flow, (6) characterize potential impacts of the regional carbonate aquifer on subregional and local flow components, (7) determine potential effects of regional

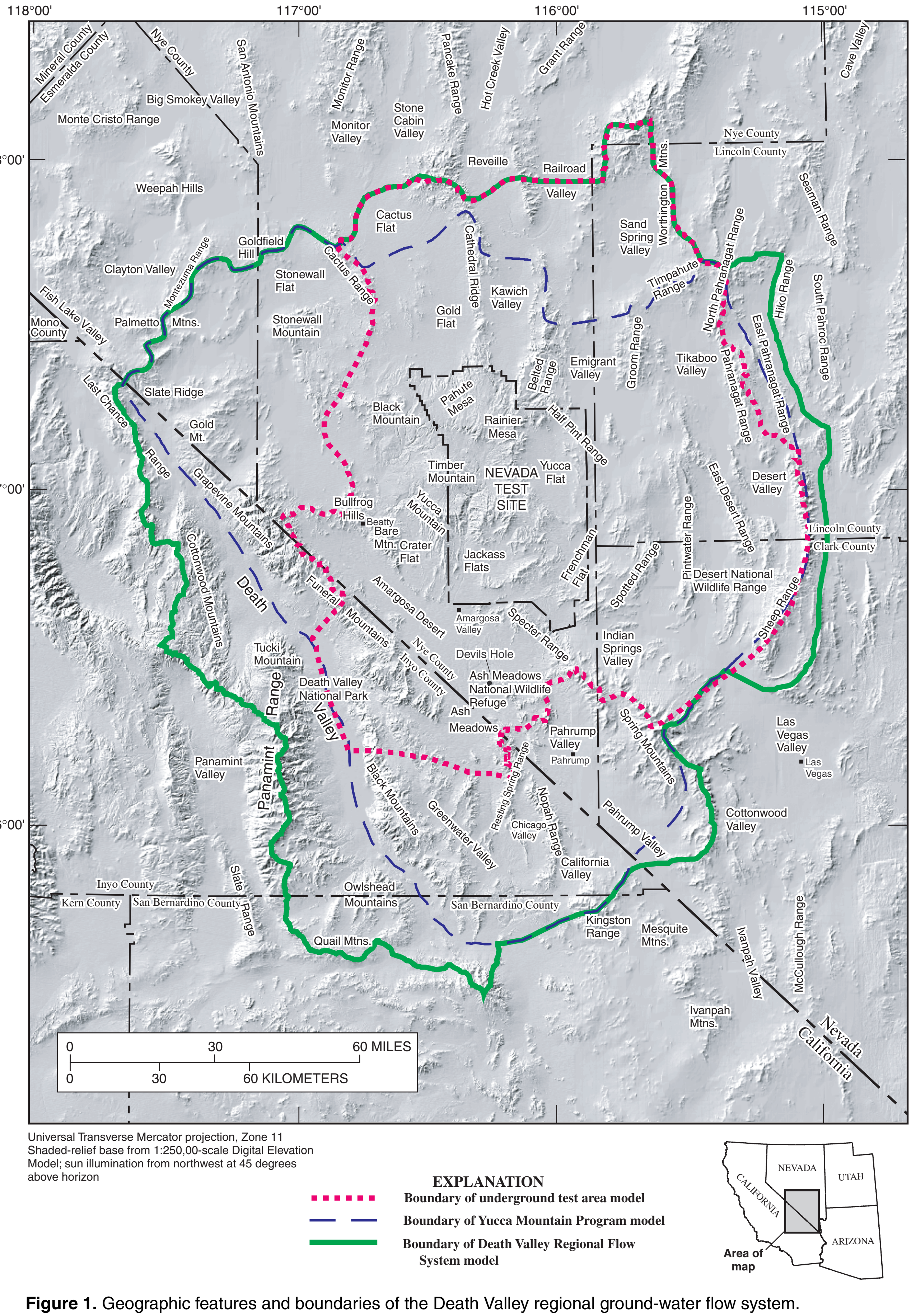

Figure 1. Geographic features and boundaries of the Death Valley regional ground-water flow system.

geologic structure on the flow system, (8) establish regional hydrologic boundaries of ground-water resources that may be unsafe for domestic or municipal use, and (9) prioritize ongoing local investigations.

Steady-state and time-dependent (transient) numerical ground-water flow models are being developed by the USGS to integrate and expand upon the existing ground-water models (Frank D'Agnese, U.S. Geological Survey, written commun., 2001). The USGS has compiled, analyzed, and synthesized hydraulic-property estimates for rocks and sediments within the Death Valley region for the basis of assigning hydraulic-property values to the various hydrogeologic units within the study area.

Location and Topography

The Death Valley regional ground-water flow system (DVRFS) is located within the Great Basin section of the Basin and Range physiographic province in southeastern California and southern Nevada between latitudes 35° and 38°15′ north and longitudes 115° and 117°45′ west (fig. 1). The topography typically consists of northerly and northwesterly trending mountain ranges separated by broad sediment-filled basins. The Spring Mountains, the highest topographic feature in the area, rise to about 3,600 m above mean sea level. Other prominent topographic features within the region include the Sheep Range, Pahute Mesa, the Funeral Mountains, and the Panamint Range. The inter-mountain basins generally decrease in altitude from north to south. The lowest altitude in the study area (86 m below sea level) is in Death Valley National Park. Other areas of national importance within the study area include the Nevada Test Site (NTS), Yucca Mountain, the Ash Meadows National Wildlife Refuge, the Desert National Wildlife Refuge, and several military installations. Pahrump, Nevada, is the largest of several towns in the study area.

The DVRFS model area encompasses about 45,000 km^2. The area of the current study is significantly larger than the DVRFS model area to permit an adequate characterization of areas that contain sites important for defining hydraulic characteristics of hydrogeologic units (HGUs; fig. 2).

Purpose and Scope

The purpose of this report is to compile and statistically summarize published and unpublished hydraulic-property estimates (such as transmissivity, hydraulic conductivity, storativity, and specific storage) and to provide a statistical range of quality-assured hydraulic-property estimates for use in ongoing DVRFS simulation activities. The estimates are presented by proposed HGUs for use in a transient numerical ground-water flow model of the Death Valley region. Descriptive statistics of the estimates provide ranges and trends of the parameters for use in the model.

Previous Work

Ground-water flow in the Death Valley region was discussed and simulated independently by D'Agnese and others (1997) and IT Corporation (1996a). The two steady-state numerical models resulting from these investigations, the Yucca Mountain Project–Hydrologic Resources Management Program (YMP–HRMP) flow model (D'Agnese and others, 1997) and the Underground Test Area (UGTA) Phase I flow model (IT Corporation, 1996a), respectively, have overlapping domains (fig. 1). Both models were based on digital 3-D geologic framework models and both used 3-D finite-difference codes to simulate ground-water flow. The two models differ in the numerical codes used, the number of model layers, and the distribution of hydraulic properties within discrete layers.

Hydraulic-property estimates were compiled for use in the YMP–HRMP and UGTA ground-water flow models. Estimated values for the YMP–HRMP flow model (D'Agnese and others, 1997), however, were not developed from a hydraulic-properties database compiled as part of the simulation effort. Instead, model-layer properties were estimated from a plot of statistically distributed hydraulic properties for rock types in the Basin and Range province (Bedinger and others, 1989) as part of a study of the geology and hydrology of the province. Data compiled for their report consisted of published field and laboratory tests within the Basin and Range province, as well as general studies from rocks with similar characteristics from outside the province. Individual aquifer tests used to develop the statistical plot presented in Bedinger and others (1989) were not discussed, and no hydraulic data were evaluated.

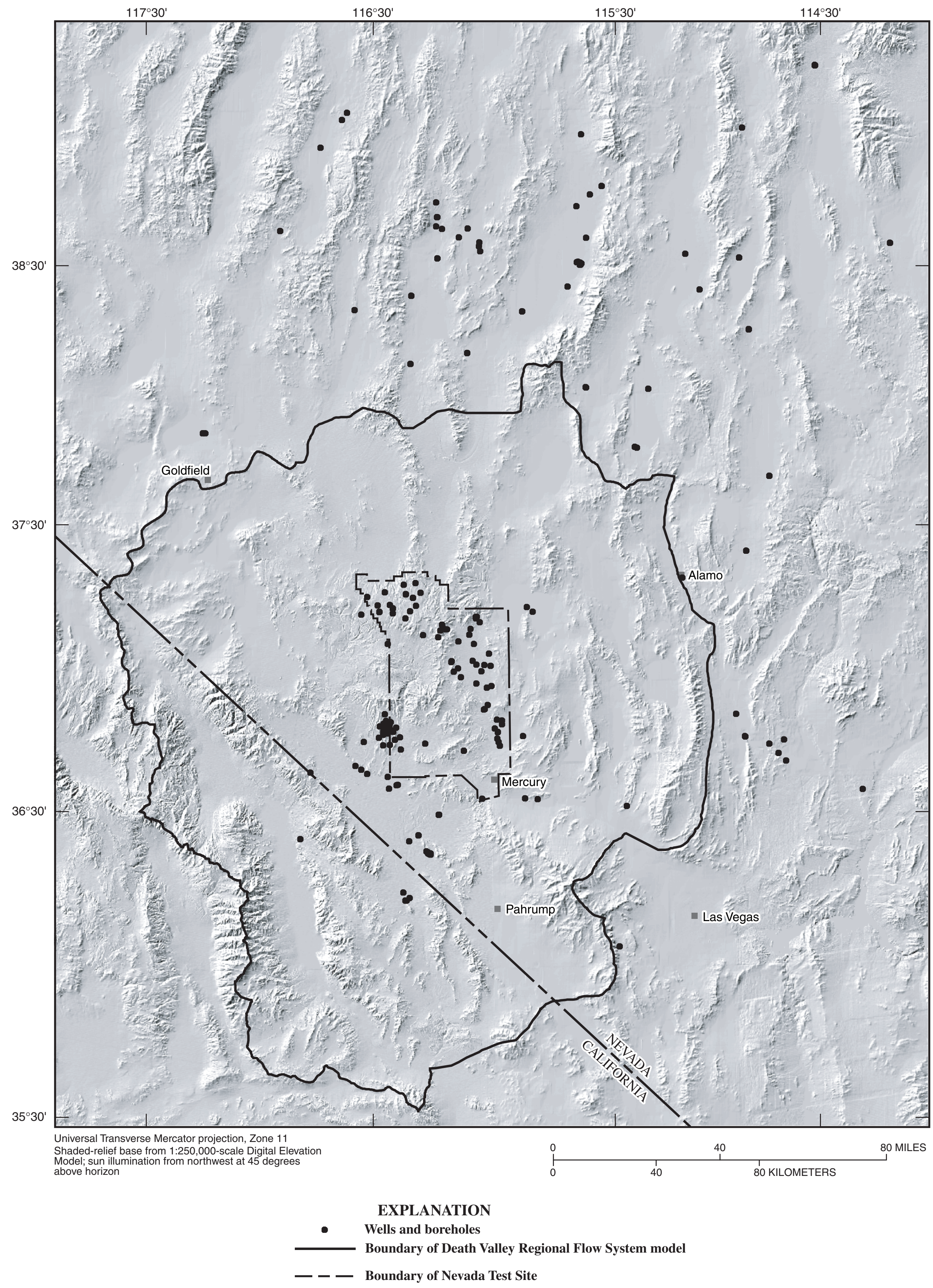

Figure 2. Locations of wells and boreholes used to determine estimates of hydraulic property.

IT Corporation (1996b) compiled a database that contains 731 analyses of transmissivity and hydraulic conductivity for the UGTA Phase I ground-water flow model. UGTA evaluated hydraulic properties from the literature (including re-interpretation of published data) and from UGTA-specific tests. Because the flow model was time independent, no values of storativity or specific yield were compiled. Databases from those simulation efforts have been expanded upon in this study.

Acknowledgments

This report is a condensed summary of the efforts Mr. Arthur L. Geldon of the Yucca Mountain Project Branch, USGS, made to compile, analyze, and interpret hydraulic-property estimates for the DVRFS. We thank Dr. Keith Halford and Mr. David Prudic (both with the U.S. Geological Survey, Carson City, Nev.), Dr. Richard Waddell (GeoTrans, Denver, Colo.), and Mr. William Fryer (IT Corporation, Las Vegas, Nev.) for their thorough and critical reviews of the initial manuscript. Their efforts have greatly enhanced the quality of this work. We also acknowledge the efforts of Mr. Robert Bangerter (U.S. Department of Energy, Environmental Restoration Program, Nevada Operations) for providing the funding to complete this work.

HYDROGEOLOGIC SETTING

The Death Valley region has an active geologic history, including intermittent marine and non-marine sedimentation, large-scale compressive deformation, plutonism, volcanism, and extensional tectonics (Stewart, 1980; Mifflin, 1988). Much of the study area has undergone deformation, and some parts have experienced nearly continuous tectonic activity since the late Proterozoic (Grose and Smith, 1989). The structural features and faulting in the region are a result of the complex interaction of the North American and Pacific lithospheric plates (Smith and Sbar, 1974; Atwater and Stock, 1998). Combinations of normal, reverse, and strike-slip faulting and folding episodes (Carr, 1988) have resulted in a complex distribution of rocks. Consequently, diverse rock types, ages, and deformational structures are often juxtaposed and subsurface conditions are variable and complex. Knowledge of the geology beneath the alluvial basins is indirect in most of the region.

The rocks of the Death Valley region are comprised of Proterozoic and Cambrian siliciclastics and metamorphics; Paleozoic siliciclastic and carbonates; Mesozoic siliciclastics and intrusives; Pliocene fluvial, paludal, and playa sedimentary deposits; Tertiary volcanics and alluvium; and Tertiary alluvium and colluvium; and Quaternary eolian deposits (Waddell, 1982). Plate 1 presents a generalized stratigraphy of the Death Valley region.

Regional Ground-Water Hydrology

Hydraulic connection between basins within the DVRFS occurs through unconsolidated sediments present atop low interbasinal topographic divides and by deep interbasinal flow beneath valley floors and adjacent mountains through fractured Paleozoic carbonate rocks (Winograd and Thordarson, 1975; Prudic and others, 1995).

Faults can disrupt stratigraphic continuity, thereby diverting water in regional circulation to subregional and local outlets. Within the Death Valley region, faults and related fractures exert the greatest influence on ground-water flowing through bedrock aquifers (Faunt, 1997).

Ground-water flow is controlled also by lithologic variability along flow paths. In basin-fill sediments, changing depositional environments over short distances may result in substantial facies changes that can affect transmissivity and hydraulic conductivity, particularly where silt and clay become intermixed or interbedded with sand and gravel (Plume, 1996). In volcanic rocks, a characteristic change from lava flows to welded tuffs and, ultimately, non-welded and bedded tuffs with increasing distance from eruptive centers can cause hydraulic properties of the stratigraphic unit to exhibit great spatial variability (Laczniak and others, 1996).

Lateral facies changes within Paleozoic rocks might affect permeability. For example, a westward facies change in Mississippian rocks from predominantly limestone and dolomite to predominantly argillite and quartzite produce a barrier to regional ground-water flow in the vicinity of the NTS (Winograd and Thordarson, 1975). Cambrian and Proterozoic clastic, igneous, and metamorphic rocks force water upward into overlying aquifers and create flow-system boundaries throughout the Death Valley region (Winograd and Thordarson, 1975).

Factors other than lithology and structure in the Death Valley region that influence permeability and ground-water flow include increasing cementation of basin-fill sediments with age and decreasing fracture volume in bedrock aquifers (Winograd and Thordarson, 1975), alteration and welding in tuffs (Laczniak and others, 1996), and the effects of hydrochemical changes in response to thermal gradients (Moore and others, 1984).

Hydrogeologic Units

Physical characteristics were used by Winograd and Thordarson (1975) to group geologic formations of hydrologic significance in the vicinity of the NTS into HGUs. The seven HGUs defined by Winograd and Thordarson (1975), from oldest to youngest are: the lower clastic aquitard (currently termed the lower confining unit); the lower carbonate-rock aquifer; the upper clastic aquitard (currently termed the upper confining unit); the upper carbonate-rock aquifer; the tuff aquifers (currently termed volcanic-rock aquifers); volcanic aquitards (currently termed the volcanic confining units); and the valley-fill aquifer (currently termed alluvial aquifer). The lower confining unit forms the basement and generally is present beneath the other units except in caldera complexes. The lower carbonate-rock aquifer is the most extensive and transmissive in the region, but does not control ground-water flow within the caldera complexes. The upper confining unit is present in the north-central section of the NTS and restricts flow between overlying and underlying units; this unit also is associated with many of the steep hydraulic gradients in and around the NTS. The upper carbonate aquifer exists where it is physically separated from the lower carbonate aquifer by the upper clastic confining unit. The volcanic-rock aquifers and the volcanic confining units form a stacked series of alternating aquifers and confining units in and around the Southwest Nevada Volcanic Field (SWNVF). The volcanic-rock aquifers are moderately transmissive and are saturated in the western section of the NTS. The alluvial aquifer, though discontinuous, forms an important regional aquifer.

The major HGUs originally defined by Winograd and Thordarson (1975) form the basis of HGUs used in previous modeling studies (D'Agnese and others, 1997; IT Corporation, 1996a), in the ongoing DVRFS transient modeling study (Claudia Faunt, U.S. Geological Survey, written commun., 2001), and in this report. Although all the major geological features were retained, many of the smaller geologic units were grouped into larger entities by generalizing lithologic and hydrologic properties of the formations (fig. 3). Furthermore, the categorization of aquifers and confining units as distinct strata fails to account for structurally and lithologically controlled variations in hydraulic properties within geologic units and vertical ground-water flow between geologic units with different lithologies. On a regional scale, those factors exert strong influences on ground-water flow. While these terms are a useful designation, readers are cautioned about inferring hydraulic properties for a particular HGU, generally obtained from local-scale tests, to the hydraulic connectivity regional scale.

The DVRFS transient modeling study has further subdivided the unconsolidated sediments and consolidated rocks into 19 HGUs (table 1). For the purposes of this study, several of the DVRFS transient model HGUs were combined into a single HGU, such that a total of 11 HGUs are used (table 1). Each of the 11 HGUs has a quasi-uniform geological, structural, and hydrological characteristic and is laterally extensive.

DATA ANALYSIS AND SYNTHESIS

In this study, all aquifer-test results compiled from published reports were verified by re-analyzing the aquifer-test data using analytical solutions appropriate to the hydrogeologic setting in which those tests were conducted. If the published results agreed to within a factor of 2, the published results were accepted. If the difference between the published data and the independent calculations exceeded a factor of 2, and no independent justification was found for using the published data, the calculated values were reported. Because of the uncertainty associated with converting specific capacity data to transmissivity values, specific capacity data were not used. Because of the low volume of geologic material samples, results from the permeameter tests were not used in the analyses discussed in this report (with the exception of the clastic confining units). Following the elimination of suspect data and the addition of newly analyzed data, statistical methods were used to evaluate the distribution of hydraulic properties in the 11 DVRFS derived HGUs. Except for wells located on the Colorado Plateau in Utah, figure 2 shows the locations of the wells and boreholes used to collect data for the estimation of

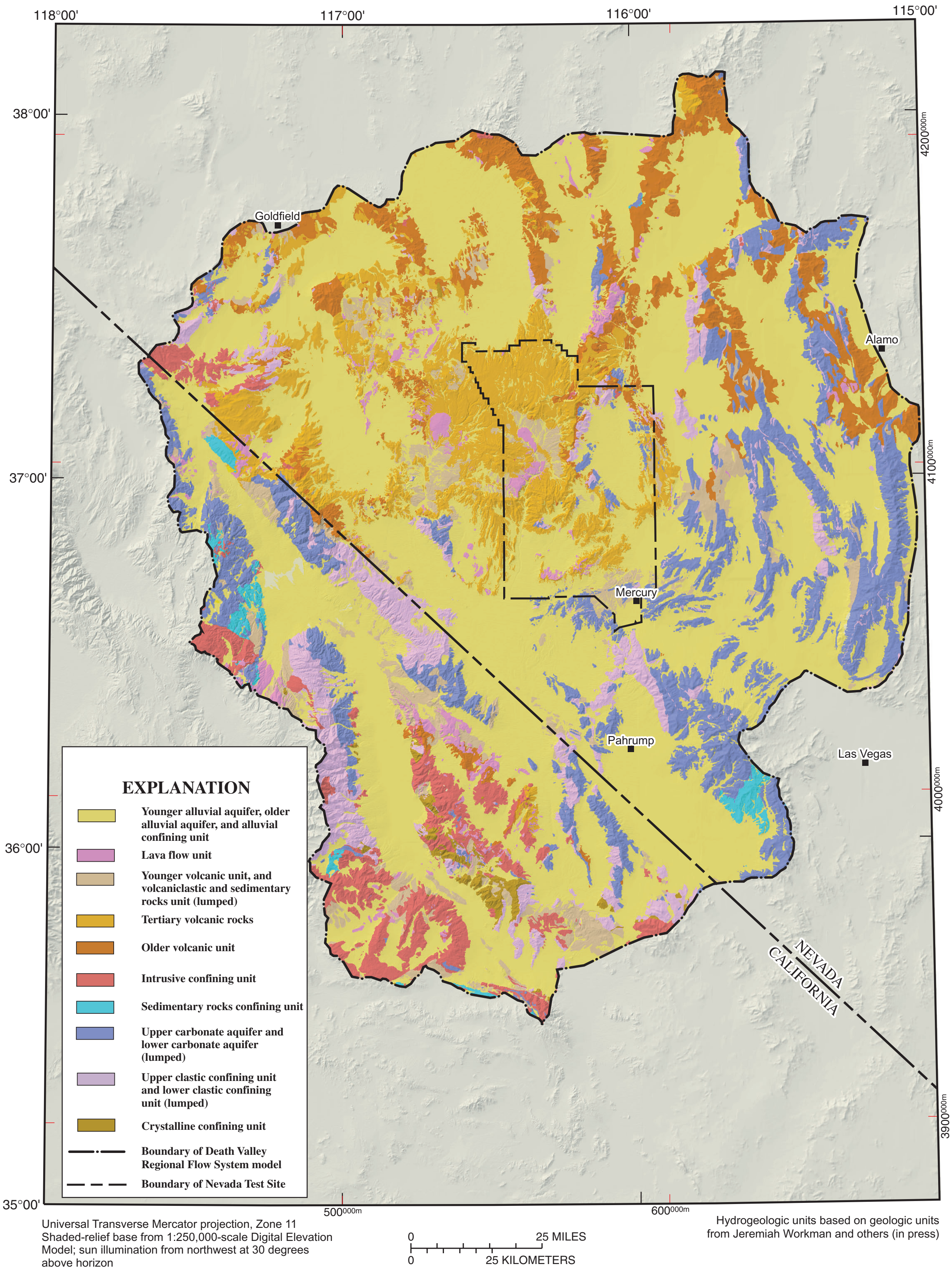

Figure 3. Surface distribution of hydrogeologic units in the Death Valley region.

Table 1. Geologic units and hydrogeologic units in the Death Valley regional ground-water flow system (DVRFS)

Hydrogeologic unit (this report)	Representative geologic units	Proposed transient DVRFS hydrogeologic unit [1]
Younger and older alluvial aquifers (YAA and OAA)	Quaternary stream-channel alluvium Quaternary eolian deposits Quaternary-Tertiary fan alluvium Quaternary-Tertiary landslide deposits	Younger alluvial aquifer (YAA) Older alluvial aquifer (OAA)
Alluvial confining unit (ACU)	Quaternary-Tertiary lacustrine and playa sediments; Quaternary-Tertiary spring-carbonate deposits	Alluvial confining unit (ACU)
Lava flow unit (LFU)	Basalt of Crater Flat-Amargosa Valley area Basalt of Jackass Flats Post-Thirsty Canyon basalt flows Funeral Formation Basalt of Lunar Crater area	Lava flow unit (LFU)
Younger volcanic unit and volcaniclastic and sedimentary rocks unit (YVU and VSU)	Furnace Creek Formation Artist Drive Formation Muddy Creek Formation Horse Spring Formation Pavits Spring Formation Panuga Formation Amargosa Valley Formation Titus Canyon Formation Sheep Pass Formation	Younger volcanic unit (YVU) Volcaniclastic and sedimentary rocks unit (VSU)
Tertiary volcanic rocks	Volcanics of Fortymile Canyon Volcanics of Stonewall Mountain Thirsty Canyon Group Timber Mountain Group Paintbrush Group Crater Flat Group Belted Range Group Calico Hils Formation Wahmonie Formation	Thirsty Canyon/Timber Mountain volcanic aquifer (TMVA) Paintbrush volcanic aquifer (PVA) Calico Hills volcanic unit (CHVU) Wahmonie volcanic unit (WVU) Belted Range/Crater Flat unit (BRCFU)
Older volcanic unit (OVU)	Kane Wash Tuff Tub Spring Tuff Hiko Tuff Shingle Pass Tuff Monotony Tuff Volcanics of Quartz Mountain Volcanic of Oak Spring Butte Volcanics of Kawich Valley Tunnel Formation Leach Canyon Formation Pahranagat Formation Tuff of Williams Ridge and Morey Peak	Older volcanic unit (OVU)
Intrusive confining unit (ICU)	Tertiary intrusive rocks Cretaceous intrusive rocks Jurassic intrusive rocks	Intrusive confining unit (ICU)

Table 1. Geologic units and hydrogeologic units in the Death Valley regional ground-water flow system (DVRFS)— Continued

Hydrogeologic unit (this report)	Representative geologic units	Proposed transient DVRFS hydrogeologic unit [1]
Sedimentary rocks confining unit (SCU)	Chinle Formation Moenkopi Formation Kaibab Limestone Toroweap Formation Permian redbeds	Sedimentary rocks confining unit (SCU)
Upper and lower carbonate aquifer (UCA and LCA)	Monte Cristo Group Pogonip Group Joana Limestone Guilmette Formation Nopah Formation Bonanza King Formation Carrara Formation Ely Springs Dolomite Bird Spring Formation Simonson Dolomite Sevy Dolomite Laketown Dolomite Ely Springs Dolomite	Upper carbonate aquifer (UCA) Lower carbonate aquifer (LCA)
Upper and lower clastic confining units (UCCU and LCCU)	Eleana Formation Chainman Shale Johnnie Formation Pilot Shale Wood Canyon Formation Zabriskie Quartzite Stirling Quartzite Pahrump Group	Upper clastic confining unit (UCCU) Lower clastic confining unit (LCCU)
Crystalline confining unit (XCU)	Middle Proterozoic igneous and metamorphic rocks	Crystalline confining unit (XCU)

[1] Claudia Faunt, U.S. Geological Survey, written commun., 2001.

hydraulic properties presented in this report. The Colorado Plateau wells are not contained in the USGS National Water Information System (NWIS) database and do not have exact locations associated with them. These wells were included in the analysis of hydraulic properties because they are completed in the sedimentary confining unit (table 1), of which data are sparse in the DVRFS.

The following hydraulic parameters are the primary focus of this study because of their use in ongoing numerical flow-modeling studies. The parameters were defined by Lohman (1979, p. 6 and 8):

Hydraulic conductivity (unit length per unit time): The coefficient that describes the ability of a geologic medium to "… transmit in unit time a unit volume of ground water at the prevailing viscosity through a cross section of unit area, measured at right angles to the direction of flow, under a hydraulic gradient of unit change in head through unit length of flow." Hydraulic conductivity can be calculated by dividing the transmissivity by the aquifer thickness (Lohman, 1979).

Transmissivity (square unit length per unit time): "… The rate at which water of the prevailing kinematic viscosity is transmitted [horizontally] through a unit width of the aquifer under a unit hydraulic gradient."

Specific yield (unitless): "The ratio of (1) the volume of water which after being saturated, it [rock or soil] will yield by gravity to (2) its [rock or soil] own volume." Specific yield is virtually the same as the storativity for unconfined aquifers.

Storage Coefficient or Storativity (unitless): "The volume of water an aquifer releases from or takes into storage per unit surface area of the aquifer per unit change in head."

Methods Used to Analyze Aquifer Tests

Aquifer tests in unconsolidated sediments throughout the Death Valley region were analyzed by conventional methods developed for porous media (Dawson and Istok, 1991; Driscoll, 1986; Lohman, 1979). Because the consolidated sedimentary and igneous rocks of the region tend to be heavily fractured and the aquifer volume generally is large enough to permit an equivalent porous-media response to pumping, porous-media analysis methods were deemed adequate. This assumption is examined in more detail in the section "Fractured Media and Equivalent Porous Media." Once a match has been determined, a point is selected and the corresponding coordinate values for head, time, dimensionless head, and dimensionless time are selected.

Several different methods were used to analyze the data which were acquired from tests of constant-rate pumping, slug (injection and bailing), swabbing, and drill stem. Common analytical methods are briefly described below, while details can be found in the cited references. Uncommon analytical methods used in this study are cited with the aquifer-test results (app. A).

Constant-rate pumping and injection tests were analyzed by curve-fitting methods. Theoretical solutions to aquifer-test problems are represented as dimensionless curves. Data in the form of water levels or recovery are plotted as a function of elapsed time on log-log scales. These data curves are then matched to the dimensionless curves. These match-point values are then substituted into analytical equations to estimate hydraulic-property values. The Theis (1935) solution was used for aquifer tests in non-leaky confined aquifers. Residual drawdown in pumping tests and residual water-level rise in injection tests were analyzed to determine transmissivity, storativity, and, if the representative thickness of the aquifer is known, hydraulic conductivity. For this method, water-level change was plotted as a function of the log of the ratio of elapsed time since pumping or injection started to the elapsed time since pumping or injection ceased (Theis, 1935). The Theis method, as do those methods discussed below for confined aquifers, assumes that observation wells completely penetrate homogeneous, isotropic, confined aquifer of infinite extent. Curve-fitting techniques for estimating transmissivity and storativity for leaky, confined aquifers without storage in the confining unit were developed by Hantush and Jacob (1955) and Cooper (1963). Curve-fitting methods for estimating the transmissivity and storativity for leaky, confined aquifers with storage in the confining unit were developed by Hantush (1961) and Bourdet (1985). For unconfined aquifers with anisotropy but using the other assumptions previously mentioned for confined aquifer methods, Boulton (1963), Stallman (1965), and Neuman (1975) developed curve-fitting techniques to estimate transmissivity, anisotropy, and storativity. It should be noted that the Neuman (1975) method may not be appropriate for use with fractured rock. Fractured rock has a "dual-porosity" response that comes from the immediate de-watering of fractures (being the most permeable), followed by the delayed response of de-watering from the matrix. The Neuman (1975) method assumes that this delayed response is due to aquifer depressurization and dewatering. In fractured rock, the delayed response is believed to be from the exchange of water between fractures and matrix rock. Neuman analyses reported in the database are primarily from non-fractured media (e.g., alluvium). Where the Neuman (1975) method was applied to fractured volcanic rocks, the database (app. A) contains the previously published values. Because of the above-mentioned conditions, vertical anisotropy estimates for fractured rock using the Neuman method are suspect.

In fractured hydrogeologic media, fluid can be contributed to the system either from fractures or the matrix. This "dual-porosity" concept involves the exchange of water between the fractures and the matrix. Several specialized methods involving this concept have been developed, some of which were used in the published hydraulic-property estimates compiled for this report. The two methods whose results are reported in the database are by Moench (1984) and Streltsova-Adams (1978). Both methods use derived type curves for dual-porosity solutions to aquifer-test problems to match time-drawdown data from pumping and observation wells.

Straight-line fitting methods involve fitting a straight line through drawdown or residual drawdown data as a function of the log time or distance from the test well, and then substituting the slope of this line into analytical equations to estimate hydraulic-property values. Under the same assumptions applicable for the Theis (1935) solution, the slope of a straight-line fit to drawdown or recovery data plotted as a function of log time the values of transmissivity and storativity can be determined (Cooper and Jacob, 1946).

In bailing tests, water is bailed repeatedly for an extended period, but some recovery of water level in well occurs as the bailer is brought to the surface, emptied, and then returned to the test interval. The average withdrawal rate, which is the total volume of water removed divided by the time that the well was bailed, does not account for drainage back to the well between bailing runs or variations in the rate of bailing. In most bailing tests, residual drawdown from bailing can be analyzed using the recovery method of Theis (1935).

In swabbing tests, a mechanical device is lowered into the well to displace water. After repeated runs, the average withdrawal rate is calculated in the same way that the average bailing rate is calculated. Residual drawdown is then analyzed using the recovery method of Theis (1935).

In slug tests, a known volume of water either is instantaneously removed from or is injected into a well, and the time history of water-level recovery to the static water level is monitored. Cooper and others (1967) developed a method for analyzing slug tests, which was later modified by Bredehoeft and Papadopulos (1980). In the solution of Cooper and others (1967), ratios of the water-level drawdown or rise to the static water level (H/H_0) are plotted as a function of log time since the test was initiated. Similar to the other curve-fitting techniques previously described, the data curve is then matched to a dimensionless type curve to obtain values of hydraulic properties.

Drill-stem tests are the standard way in which hydraulic properties of potential oil and gas reservoirs are evaluated by the petroleum industry (Bredehoeft, 1965). This test measures the pressure drop as the formation fluid (such as oil) moves from an isolated section of the borehole into a drill stem lowered into the borehole. In the method of Horner (1951), fluid-pressure recovery during the second shut-in period is plotted as a function of the ratio of the time elapsed during the shut-in period and preceding flow period to the time elapsed during the shut-in period.

Statistical Analyses

Descriptive statistics, including the geometric and arithmetic means, range, and the 95-percent confidence interval (±1.96 standard deviations from the geometric mean) of the hydraulic conductivity, storage parameters, and anisotropy ratios are reported for each of the HGUs. These parameters will be used to aid in the calibration of the DVRFS transient ground-water flow model. Because hydraulic conductivity tends to be log normally distributed (Neuman, 1982), the geometric mean of the estimates is reported. The arithmetic mean also is reported. Storage parameters tend to be normally distributed (Neuman, 1982) and because of this, the arithmetic mean of the estimates is reported. Values of hydraulic conductivity derived from pumping well data, when an observation well was available, were not used in the statistical calculations to avoid bias from re-sampling the same aquifer test. For similar reasons, slug tests from intervals that overlapped each other, although present in the database (app. A), were not used in the statistical calculations.

Fractured Media and Equivalent Porous Media

Most of the analytical methods used in this work assume that an aquifer is a porous medium. However, the influence of fractures is fundamental to the flow of water in volcanic and carbonate rocks. In order to apply these aquifer-test methods to fractured rocks it is necessary to assume that the rocks are sufficiently homogeneously fractured and interconnected such that the rock being tested can be considered “an equivalent porous medium.” The spacing of fractures, as well as their interconnectivity, can affect the results of an aquifer test. In areas where fractures are tightly spaced and interconnected, transmissivities generally are higher than in areas where the fractures are widely spaced and not interconnected. In a study on transmissivity in crystalline rock, slug tests using either porous or fractured media methods, provided estimates of transmissivity within an order of magnitude of each other (Shapiro and Hsieh, 1998). In the cases examined here, the equivalent-porous-medium assumption cannot be ruled out because plots of drawdown or recovery of water levels in wells conform to type curves derived for porous media.

Effects of Test Scale on Determination of Hydraulic Properties

Hydraulic-conductivity and transmissivity estimates are functions of test scale (Dagan, 1986; Neuman, 1990). As media test volume increases, more aquifer heterogeneity is encountered and influences the test results. For example, the potential exists to involve a larger network of fractures in the aquifer response to the imposed stress. In laboratory permeameter tests of core samples for determining rock matrix properties, unfractured core is needed for successful results. Because only matrix rock properties are determined from permeameter tests, the estimates generally are not useful for regional-scale ground-water flow models of fractured-rock aquifer systems. Thus, results for permeameter tests of core samples are not utilized in the descriptive statistical calculations of the hydraulic parameters (with the exception of the clastic confining units). Similarly, slug tests only examine a relatively small amount of aquifer material adjacent to the borehole. Because of this, hydraulic-property estimates from slug tests might not be representative of an entire unit. Single-well aquifer tests (including the pumping or injection well in multiple-well tests) optimally determine hydraulic properties in the near-borehole environment, but the accuracy of these tests can be decreased by inefficient borehole construction, convergence of flow lines and related head losses as water flows into or out of sections of perforated casing, and head loss as water moves between the test-interval depth and the pump-intake depth. As such, for the same set of wells transmissivity estimates derived from single-well tests tend to be less than those of multiple-well tests. Similarly, estimates of storage coefficients from single-hole tests are less reliable than those from multiple-well tests. Multiple-well aquifer tests tend to be more reliable because they manifest the influence of field-scale features, such as faults and fractures, as well as the water-transmitting properties of the rock matrix.

The hydraulic-property estimates presented in this report are based on the results of mostly field-scale tests involving wells. These tests include only a small amount of the volume of aquifer material within an HGU and thus are testing only a very small part of the HGU. The hydraulic-property estimates presented herein are intended to serve only as the basis for constraining flow estimates obtained from the simulation process. The scaling-up of these values for use in calibrating a regional ground-water flow model is problematic and is not explicitly addressed in this report.

General Limitations

General guidelines were used for selecting hydraulic-property data for compilation. These include: (1) the use of published aquifer-test results from wells in the DVRFS area. Selected unpublished data and aquifer-test results were evaluated and analyzed to fill spatial or hydrogeologic data gaps. (2) analyses of aquifer tests using methods appropriate to regional numerical ground-water flow models and (3) analyses for each HGU should be sufficient to provide adequate spatial coverage and statistically describe variance resulting from differences in lithology, fracturing, and faulting. Based on Freund (1992), about 30 samples are a sufficient number to statistically describe parameters. Because wells and boreholes often are installed for purposes other than obtaining hydraulic-property data (such as water supply or monitoring), the above quidelines were not satisfied completely. Selected unpublished DVRFS area aquifer-test results and published data are from hydrologically similar areas.

Analytical methods used to determine the hydraulic-property estimates presented in this report rely on assumptions about the type and configuration of the aquifer. These assumptions are necessary to simplify the flow system so that mathematical equations representing ground-water flow can be solved analytically but result in some uncertainty in the computed hydraulic properties.

Most analytical methods assume that flow to a pumping well is derived from an aquifer of infinite extent. This assumption may not be accurate for many aquifer tests presented in this report because of faults in the study area that may act as either recharge or barrier boundaries.

The most commonly applied analytical methods for pumping tests in the study area, those of Theis (1935) and Cooper and Jacob (1946), assume radial flow to the pumping well under an axisymmetric hydraulic gradient. However, because of media heterogeneities, hydraulic gradients may vary directionally. Differing results in hydraulic-property values obtained from multiple-well aquifer tests involving multiple observation wells may arise as a result of non-radial flow occurring in a part of the flow system monitored by one or more, but not all observation wells. Disregarding a non-uniform hydraulic gradient seemingly would result in inaccurate computations of hydraulic properties, if the solutions of Theis (1935) or Cooper and Jacob (1946) are used. Only a single estimate of transmissivity and storage properties should be reported for these particular tests. To obtain these single results, the average of the property estimates could be used. Because the purpose of this report is to compile and report on estimates of hydraulic properties for use with a numerical flow model, all estimates are considered to be independent with respect to the descriptive statistics (central tendency and spread). Estimates from a pumping well are excluded when one or more observation wells were available due to inaccuracies inherent in the pumping well estimates. Several estimates from the same well (in the case of packer tests) or the same test (in the case of multiple observation wells) can give a range of values reflecting varying material properties of the unit. It is reasoned that because the statistics describe the central tendency and the spread of these parameters for a particular unit, use of most the estimates is appropriate (except where tested intervals straddle each other). One limitation to this approach is that the statistics may be biased toward the estimates obtained from multiple-well tests.

Single-well pumping or slug tests can provide estimates of storativity. These estimates, however, may vary up to an order of magnitude of the actual value (Cooper and others, 1967, p. 267). The slug-test solution of Cooper and others used in these analyses is very insensitive to storativity. Storativity values calculated from slug tests were not used in the statistical summaries of the hydraulic-property estimates and are not reported in the database.

Spatial bias could be significant for the hydraulic-property estimates compiled in this report. Wells and boreholes were drilled to meet the original goals of their respective studies, not to collect data to determine statistically representative regional-scale hydraulic properties. Most information was collected from wells clustered around Yucca Mountain and the NTS. Data were collected for studies of these areas and the number of wells decreases away from these areas. Many wells also were installed in relatively shallow formations because of the difficulties and cost associated with drilling deep wells.

Limitations Regarding Hydraulic Conductivity Estimates

To obtain hydraulic-conductivity estimates for use in the calibration of the DVRFS model, transmissivity estimates were divided by the thickness or length of the open interval of the tested or monitored well or borehole. The aquifer thickness was not used as this generally was unknown. Because most wells are open to the productive intervals, in a heterogeneous aquifer, coupled with usage of the open-interval thickness, hydraulic-conductivity estimates may be biased toward the larger values. Thus, the statistical means and variances presented here may be only representative of the hydraulic properties of the more productive zones within an HGU.

Other limitations of the hydraulic-property estimates involve the variability inherent in the hydrogeologic media. Lithologic factors, such as facies changes in sedimentary rock, welding in volcanic rocks, and degree of fracturing can cause hydraulic properties to vary greatly over relatively short distances. Variability also can be caused by sampling biases. For example, differences in the overlap between lithologic or sedimentologic bedding and the tested interval can cause estimates of hydraulic conductivity to vary. Sampling variability also can arise in fractured rocks as a result of a borehole failing to penetrate rock fractures especially for vertical boreholes penetrating rocks with steeply dipping (subvertical) fractures. Because of the inherent nature of variability, longer-term aquifer tests typically will produce more representative hydraulic-property estimates (hydraulic conductivity and storativity) than shorter-term aquifer tests or tests with shorter screened intervals (such as packer tests). Because of this, a smaller statistical constraint on the parameter estimates during calibration of the DVRFS model where this condition applies.

HYDRAULIC PROPERTIES

The hydraulic-property estimates from aquifer-test results are statistically summarized for each of the HGUs in the hydrogeologic framework of the DVRFS. Horizontal hydraulic conductivity values are presented for all tests; specific yield and storativity values are presented for each HGU, if available. A summary of the hydraulic conductivity estimates of HGUs and subunits for HGUs are presented in table 2. A compilation of hydraulic-property estimates is provided in appendix A.

Younger Alluvial Aquifer and Older Alluvial Aquifer

Most basin-fill sediments are included in the younger alluvial aquifer (YAA) and the older alluvial Aquifer (OAA; fig. 3). The YAA and OAA consist of Holocene to Pliocene sand, gravelly sand, sandy gravel, and gravel, with cobbles, boulders, silty to clayey intervals, and thin interbeds of clay and silt, that

Table 2. Hydraulic conductivity distribution in Death Valley regional ground-water flow system hydrogeologic units

[Abbreviations: —, no data; m/d, meters per day; ACU, alluvial confining unit; BRU, Belted Range unit; CFVU, Crater Flat volcanic unit; ICU, intrusive confining unit; K, hydraulic conductivity in meters per day; LCA, lower carbonate aquifer; LCCU, lower clastic confining unit; LFU, lava flow unit; OAA, older alluvial aquifer; OVU, older volcanic unit; PVA, Paintbrush volcanic aquifer; SCU, sedimentary rocks confining unit; TMVA, Thirsty Canyon/Timber Mountain volcanic aquifer; TV, Tertiary volcanic rocks; UCA, upper carbonate aquifer; UCCU, upper clastic confining unit; VSU, volcaniclastic and sedimentary rocks unit; XCU, crystalline confining unit; YAA, younger alluvial aquifer; YVU, younger volcanic unit]

Hydrogeologic unit or subunit	Geometric mean K (m/d)	Arithmetic mean K (m/d)	Minimum K (m/d)	Maximum K (m/d)	95-percent confidence interval of geometric mean (m/d)	Number of analyses
YAA and OAA	2	11	0.001	130	0.6 – 4	43
ACU	3	11	.003	34	.6 – 10	13
LFU	—	—	.002	4	—	2
YVU and VSU	.06	1.5	.00004	6	.01 – .4	15
TV	.1	4	.000001	180	.08 – .2	159
Rhyolitic to rhyodacitic lava flows	.1	.6	.000007	4	.04 – .4	25
Ash-flow tuff	.1	5	.000002	180	.06 – .2	109
Non-welded to partially welded	.06	7	.003	180	.03 – .2	43
Partially to moderately welded	.04	1	.000002	19	.03 – .1	35
Moderately to densely welded	2	13	.02	55	.18 – 15	7
Unaltered	.4	8	.00002	180	.2 – .9	71
Zeolitized and argillized	.04	1	.000002	25	.02 – .08	63
Tuff breccia and ash-flow tuff	.3	4	.0008	15	.03 – 3	11
Bedded ash-fall and reworked tuff and ash-flow tuff	.1	2	.00009	15	.03 – .7	14
TMVA	.01	2	.0002	20	.001 – .01	11
PVA	.02	4	.000007	22	.001 – .09	9
CHVU	.2	.6	.008	2	.08 – .5	14
BRU	.3	1	.01	4	.06 – 2	6
CFVU	.2	6	.000002	180	.09 – .3	91
OVU	.004	.07	.000001	1	.001 – .01	46
ICU	.01	.3	.0006	1	.001 – .01	7
SCU	.002	.02	.0002	.3	.0007 – .005	16
UCA and LCA	.6	90	.00001	820	.2 – 2	51
Faulted and karstic	3	120	.01	820	3 – 4	18
Unfaulted	.1	2	.0001	14	.02 – .5	19
UCCU and LCCU	.00003	.2	.00000003	5	.000003 – .0003	30
UCCU (shales)	.01	.07	.0003	.4	.002 – .06	9
LCCU (quartzites)	.0000006	5	.00000003	5	.00000007 – .000005	19
XCU	—	—	.00000002	[1]<.4	—	—

[1] Based on the 14.5 percent upper confidence level of Bedinger and others (1989) weathered metamorphic rocks hydraulic conductivities, and the lower 14.5 percent estimate for deep unweathered metamorphic rocks. Confidence levels are based on the 50th percentile estimate of their sample.

were deposited mostly in alluvial fans, floodplains, and stream channels. Eolian silt and sand, landslide deposits, debris flows, talus, colluvium, basalt flows, and tuff layers are present locally (that is, are discontinuous and not considered regional, areal-extensive units). Sediments generally are uncemented at and near the water table, but become more indurated with increasing depth. This combined HGU tends to be an aquifer where present, but finer grained sediments and intercalated volcanics locally can impede ground-water movement.

Forty-three analyses of hydraulic properties were compiled for the combined YAA and OAA, 25 from single-well aquifer tests and 18 from multiple-well aquifer tests. Tested intervals of the boreholes ranged from 6 to 161 m. Aquifer-test pumping rates ranged from 0.5 to 84 L/s with a minimum pumping time of 91 minutes. Aquifer-test analyses for pumping wells were omitted from the statistical summary, when an observation well was available to avoid biasing.

The horizontal hydraulic-conductivity values ranged from 0.001 to 130 m/d with geometric and arithmetic means of 2 m/d and 11 m/d, respectively. The 95-percent confidence interval about the geometric mean for these values ranged from 0.6 to 4 m/d.

Specific-yield estimates from late-time data (water levels measured near the end of the aquifer test), estimated in 14 analyses using Neuman (1975). These estimates ranged from 0.0004 to 0.2 with an arithmetic mean of 0.03 with the low value excluded (the low minimum value of 0.0004 suggests that the Neuman (1975) method was not applicable because of possible aquifer heterogeneity or dual-porosity conditions).

Alluvial Confining Unit

The alluvial confining unit (ACU) consists of Holocene to Pliocene playa, lake, marsh, and spring-deposited clay, marl, limestone, silt, sand, gravel; evaporite deposits, and thin tuff layers. The ACU tends to be a regional confining unit, but limestone and sand layers can be productive local aquifers, although the limestone component is probably limited in areal extent. The ACU is restricted to the topographically lowest areas of structural basins in the Death Valley region (fig. 3). Sediments that comprise the ACU may interfinger with those of the YAA and OAA, can be absent with depth, or may be present elsewhere beneath deposits of sand and gravel. The YAA and OAA and the ACU are shown as a single unit in figure 3.

Fifteen analyses of hydraulic properties were compiled for the ACU, 7 from single-well aquifer tests and 8 from multiple-well aquifer tests from 12 wells in the Amargosa Desert and Cave Valley. Test-interval thicknesses ranged from 0.3 to 235 m. Aquifer-test pumping rates ranged from 14 to 114 L/s with a minimum pumping time of 160 minutes. To avoid biasing, aquifer-test analyses for pumping wells were omitted from the statistical summary when an observation well was available.

Horizontal hydraulic-conductivity values ranged from 0.003 to 34 m/d with geometric and arithmetic means of 3 m/d and 11 m/d, respectively. The 95-percent confidence interval about the geometric mean for these values ranged from 0.6 to 10 m/d. The high value of 34 m/d was for a well in the Amargosa Desert and may reflect the hydraulic properties of spring-carbonate deposits, rather than clayey playa deposits.

Estimates of the horizontal hydraulic conductivity (app. A) for the ACU unit are equal or slightly greater than those of the YAA and OAA units. This result appears to be counter intuitive since confining units are expected to have hydraulic conductivities significantly lower than those of aquifers. However, the wells used for the ACU aquifer tests may be completed in more permeable alluvial deposits rather than playa deposits of lower permeability. Thomas and others (1989) indicate that playa deposits within the Smith Creek Valley in Lander County, Nev., possess vertical hydraulic-conductivity values of about 0.03 m/d, which suggests that the hydraulic conductivity of playa deposits is much less than that estimated for this unit using estimates from within the DVRFS.

Storativity values from seven analyses ranged from 0.00009 to 0.04 with an arithmetic mean of 0.01 (app. A). The specific yield from one analysis was estimated to be 0.01 (app. A). The apparent overlap of storativity and specific-yield values for this HGU may indicate that ground water in the ACU is variably confined, semi-confined, or unconfined.

Lava Flow Unit

The lava flow unit (LFU) consists of Holocene to Miocene basaltic and rhyolitic lava flows (typically with interbedded tuffs) interbedded with, and underlying, basin-fill sediments as well as localized cinder cones in topographic basins (fig. 3). Individual lava flows are not laterally extensive. Cinder cones typically are above the water table. Figure 3 includes some rhyolitic to rhyodacitic lava flows assigned to underlying volcanic HGUs and omits older basalt and andesite lava flows that do not have surface exposure.

Only two hydraulic-property analyses were conducted in the LFU at two separate locations. One analysis was from a single-well pumping test and the other from a slug-injection test. Test-interval thicknesses for the boreholes ranged from 61 to 80 m. For the pumping test the well was pumped at a rate of 8.4 L/s for 220 minutes. The horizontal hydraulic-conductivity value from this test was 4 m/d. The horizontal hydraulic-conductivity estimate from the slug test was 0.002 m/d. Because of the small number of hydraulic-property estimates available for this unit, estimates for the lava-flow component of the Tertiary volcanics HGU may be useful for numerical simulation of the LFU (see "Tertiary Volcanic Rocks").

Younger Volcanic Unit and Volcaniclastic and Sedimentary Rocks Unit

The younger volcanic unit (YVU) and the volcaniclastic and sedimentary rocks unit (VSU) consists of Pliocene to Eocene variably cemented conglomerate, gravelly sandstone, sandstone, siltstone, shale, calcareous shale, limestone, and intercalated tuff layers. The YVU and the VSU consist of erosional and faulted remnants of sedimentary rocks deposited in diverse terrestrial settings within syntectonic basins (fig. 3). Coarser-grained rocks, if not permeated by calcite or other cementing minerals, can be very productive aquifers. Finer-grained rocks typically impede ground-water flow over large areas. With decreasing cementation, lithologies comprising this HGU grade into those in the YAA, the OAA, and the ACU. The YVU and the VSU are considered as separate units in the DVRFS hydrogeologic framework but are combined in this report (table 1).

Fifteen analyses of hydraulic properties were compiled for the YVU and VSU, all of which represent single-well aquifer tests. Test-interval thicknesses ranged from 8 to 70 m. Aquifer-test pumping rates ranged from 0.2 to 41 L/s with a minimum pumping time of 180 minutes.

Horizontal hydraulic-conductivity values for the YVU and the VSU ranged from 0.00004 to 6 m/d with geometric and arithmetic means of 0.06 m/d and 1.5 m/d, respectively. The 95-percent confidence interval about the geometric mean of the horizontal hydraulic-conductivity values ranged from 0.01 to 0.4 m/d. Storativity was estimated from one aquifer test to be 0.006 (app. A).

Tertiary Volcanic Rocks

The Tertiary volcanic rocks unit (TV) consists of Pliocene to Miocene non-welded to densely welded ash-flow tuff, depositional and fault-related tuff breccia, ash-fall tuff, reworked tuff, volcaniclastic rocks, and rhyolite, comendite, and trachyte lava flows. This HGU represents a combination of several proposed hydrogeologic units for the transient DVRFS flow model and includes the Thirsty Canyon/Timber Mountain volcanic aquifer (TMVA), the Paintbrush volcanic aquifer (PVA), the Calico Hills volcanic unit (CHVU), the Wahmonie volcanic unit (WVU), the Belted Range unit (BRU), and the Crater Flat volcanic unit (CFVU). The volcanic rocks that comprise this HGU tend to have both fracture and matrix permeability. Fracturing, which is most intense near faults, can enhance permeability (Faunt, 1997). Alteration of rock-forming minerals to zeolite, clay, carbonate, silica, and other minerals, which is most intense toward eruptive centers, can reduce permeability (Laczniak and others, 1996). Therefore, hydraulic properties within this HGU are extremely variable laterally and with depth. Moreover, certain combinations of lithology and structure can result in very transmissive intervals or as major impediments to ground-water flow over large areas. The Tertiary volcanics unit is widely distributed in the west-central part of the Death Valley region (fig. 3). The distribution of this HGU is controlled largely by the extent of nested calderas from which middle Miocene and younger volcanic rocks of the SWNVF erupted. The Tertiary volcanics intertongue with the YAA, the OAA, the ACU, the YVU, and the VSU.

One-hundred fifty-nine analyses of hydraulic properties were compiled for the Tertiary volcanics, 116 from single-well aquifer tests and 43 from multiple-well aquifer tests. Test-interval thicknesses for boreholes screened in the Tertiary volcanics ranged from 7 m to almost 1,600 m. Aquifer-test pumping rates ranged from 0.1 to 44 L/s with a minimum pumping time of 89 minutes. To avoid biasing, aquifer-test analyses for pumping wells were omitted from the statistical summary when an observation well was available and slug-injection tests conducted over a number of smaller intervals within a larger interval also were omitted.

Horizontal hydraulic-conductivity values ranged from 0.000001 to 180 m/d with geometric and arithmetic means of 0.1 m/d and 4 m/d, respectively. The 95-percent confidence interval about the geometric mean for these values ranged from 0.08 to 0.2 m/d.

The hydraulic-conductivity estimates also were assigned to the corresponding lithostratigraphic formation or group (corresponding to the DVRFS units) and statistically summarized. Tests in wells with open intervals contained in more than one of these proposed HGUs were not used in the statistical summaries. No data were obtained for the WVU. Table 2 presents the geometric mean for the various lithostratigraphically based hydrogeologic units within the Tertiary volcanics.

Four categories of rock were recognized as a basis for evaluating lithology as an influence on hydraulic conductivity: (1) non-welded to densely welded ash-flow tuff (85 analyses); (2) rhyolite, rhyodacite, and trachyte lava flows with or without a tuff component (25 analyses); (3) tuff breccia with or without a tuff component (15 analyses); and (4) bedded tuff with or without an ash-flow tuff component (15 analyses). The presence of tuff intercalated with other rock types was unavoidable because of limitations in available data. However, the presence of tuff interbeds in intervals consisting mostly of lava flows is considered inconsequential hydraulically. Despite some ambiguity in the data (mainly from variability in the rock property descriptions for the test intervals), it appears that ash-flow tuffs, bedded tuffs, and lava flows are about equally permeable and that all of these lithologies are less permeable than tuff breccias (table 2). Ubiquitous zeolitic and argillic alteration of bedded tuff probably controls the hydraulic properties of test intervals containing bedded tuff and ash-flow tuff (Laczniak and others, 1996, p. 26).

To assess the effect of the degree of welding of ash-flow tuff on hydraulic conductivity, the results of 85 analyses of hydraulic conductivity were categorized by rock type (table 2). Three categories were selected: (1) non-welded to partially welded tuff (43 analyses); (2) partially to moderately welded tuff (35 analyses); and (3) moderately to densely welded tuff (7 analyses). Overlapping rock types, such as non-welded to densely welded tuff, were omitted from the analysis. The hydraulic conductivity of ash-flow tuff generally increases as the degree of welding increases (table 2). This welding increases the propensity of the ash-flow tuffs to fracture, which enhances permeability (Laczniak and others, 1996, p. 25).

On the basis of qualitative descriptions in borehole lithologic logs, ash-flow tuff, bedded tuff, and tuff breccia (omitting lava flows) were combined into two rock categories, unaltered tuff (71 analyses) and altered (zeolitized or argillized) tuff (63 analyses). Clay minerals from the alteration tend to reduce permeability (Laczniak and others, 1996, p. 26). Test intervals of partly altered tuff were omitted from the analysis. Results of the analyses of 134 samples suggest that the mean horizontal hydraulic conductivity of unaltered tuff is greater than altered tuff by about an order of magnitude (table 2).

Storativity in 45 analyses of aquifer tests from the Tertiary volcanics ranged from 0.00004 to 0.004 with an arithmetic mean of 0.001 (app. A). Specific yield from 10 analyses for the Tertiary volcanics ranged from 0.001 to 0.2 with an arithmetic mean of 0.03 (app. A).

Older Volcanic Unit

The older volcanic unit (OVU) consists mostly of Miocene to Oligocene ash-flow tuff, ash-fall tuff, reworked tuff, tuff breccia, volcaniclastic rocks, rhyolite, comendite, rhyodacite, and dacite lava flows, and shale, sandstone, and conglomerate of sedimentary origin. The volcanic rocks that comprise the OVU tend to have both fracture and matrix permeability. Ash-flow tuffs tend to be non-welded, but can be partly to densely welded. Alteration of ash-flow, ash-fall, and reworked tuffs to zeolite, clay, carbonate, silica, and other minerals is common. The OVU tends to be a regional confining unit and has widespread outcrop exposure in the northern part of the Death Valley region (fig. 3). Older tuffs and lava flows of the OVU also underlie the YVU and the VSU where they are present throughout the NTS. These older tuffs and lava flows can pinch out and intertongue with Tertiary sedimentary rocks in areas such as the southern end of Yucca Mountain (R.W. Spengler, U.S. Geological Survey, written commun., 2001) and between the Bullfrog Hills and Grapevine Mountains (Snow and Lux, 1999).

Forty-six analyses of hydraulic properties were compiled for the OVU, all of which were single-well tests. Test-interval thicknesses ranged from 6 to 1,054 m. Aquifer-test pumping rates ranged from 0.2 to 22 L/s with a minimum pumping time of 620 minutes. Available analyses are spatially well distributed from Railroad Valley to Monitor Valley, immediately north of the Death Valley region model area (figs. 1 and 2), but are spatially restricted from Yucca Flat and Pahute Mesa to Yucca Mountain.

Formations comprising the OVU were among the first volcanic rocks penetrated in shafts and boreholes completed at the NTS to conduct underground nuclear tests (Winograd and Thordarson, 1975). Because these rocks produced little water, Winograd and Thordarson (1975) designated them “the tuff aquitard.” Where these rocks produced water, production was erratic and attributed to interconnection of fractures in the aquitard with overlying or underlying aquifers (Winograd and Thordarson, 1975, p. 52). Only eight constant-rate pumping and injection tests were available. Aquifer-test results for OVU probably underestimate its transmissive properties because the estimates come from tests which only sample a relatively small amount of the aquifer.

Horizontal hydraulic-conductivity estimates for OVU ranged from 0.000001 to 1 m/d with geometric and arithmetic means of 0.004 m/d and 0.07 m/d, respectively. The 95-percent confidence interval about the geometric mean for these values ranged from 0.001 to 0.01 m/d. No storativity or specific yield estimates were available.

Intrusive Confining Unit

The rocks of the intrusive confining unit (ICU) consist of Jurassic to Oligocene granodiorite, quartz monzonite, granite, and tonalite. The ICU granitic rocks generally are limited in exposure within the DVRFS (fig. 3). Although these intrusive rocks can produce small quantities of water from fractures and weathered zones where present, they generally impede ground-water flow. In most of the DVRFS, Tertiary and Jurassic granitic rocks occur as small stocks, such as the Climax Stock in Yucca Flat and the Gold Meadows Stock on Rainier Mesa (Houser and others, 1961). On both sides of Death Valley, intrusive bodies are larger, more irregular in shape, and more common than elsewhere in the Death Valley region (Grose and Smith, 1989).

Few aquifer tests have been conducted in this unit in or near the DVRFS. Seven analyses were completed using slug tests, swabbing tests, and a constant-rate injection test in wells at the Climax and Belmont Stocks. Test-interval thicknesses ranged from 8 to 416 m. The injection rate for the constant-rate injection was 4 L/s for 97 minutes.

Horizontal hydraulic-conductivity values estimated for the ICU ranged from 0.0006 to 1 m/d with geometric and arithmetic means of 0.01 m/d and 0.3 m/d, respectively. The 95-percent confidence interval about the geometric mean for these values ranged from 0.001 to 0.01 m/d. No storativity estimates were obtained.

Sedimentary Rocks Confining Unit

The sedimentary rocks confining unit (SCU) consists of Permian to Jurassic interbedded conglomerate, gravelly sandstone, sandstone, siltstone, shale, calcareous shale, limestone, and gypsum. Hydraulic properties are extremely variable. The Shinarump Conglomerate and the Kaibab Limestone are regional aquifers. Other sandstone and limestone intervals transmit water locally. Intervals predominantly composed of shale, such as upper members of the Chinle Formation, are regional confining units. The SCU is exposed in the DVRFS in the upper plate of the Keystone Thrust Fault at the southern end of the Spring Mountains (fig. 1) and also is exposed just east of the DVRFS in the lower plate of the Keystone Thrust Fault in Cottonwood Valley (figs. 1 and 3). A deep well drilled to explore for oil and gas (Virgin River USA 1-A) penetrated the Moenkopi Formation and Kaibab Limestone at Mormon Mesa, just east of the DVRFS (McKay and Kepper, 1988).

Sixteen analyses were used to define the hydraulic-property estimates for the SCU. A drill-stem test from the petroleum exploration well at Mormon Mesa adjacent to the DVRFS provided the only data for this HGU. Fifteen analyses of drill-stem tests of Permian sedimentary rocks in the Colorado Plateau region of southwest Utah have been included in this report to provide additional hydraulic property estimates. The Permian sedimentary rocks of the Colorado Plateau are thought to be hydrologically similar to Mesozoic and Permian sedimentary rocks in the DVRFS because they include some of the same stratigraphic formations and have similar lithologies. Test-interval thicknesses ranged from 4 to 35 m. Aquifer-test pumping rates ranged from 0.1 to 215 L/s with a minimum pumping time of 430 minutes.

Horizontal hydraulic-conductivity values ranged from 0.0002 to 0.3 m/d with geometric and arithmetic means of 0.002 m/d and 0.02 m/d, respectively. The 95-percent confidence interval about the geometric mean for these values ranged from 0.0007 to 0.005 m/d. No estimates of storativities were obtained for the SCU.

Upper Carbonate Aquifer and Lower Carbonate Aquifer

The upper carbonate aquifer (UCA) and the lower carbonate aquifer (LCA) interfinger with the upper and lower clastic confining units. The UCA and LCA are Cambrian to Permian carbonate rocks consisting of cherty, siliceous, silty, shaly, and fine-grained limestone and cherty, silty, sandy, and fine-grained dolomite with subordinate chert, shale, siltstone, sandstone, and quartzite. Although clastic intervals confine flow, limestones and dolomites contained in these strata are aquifers that are present in the eastern two-thirds of the Great Basin (Harrill and Prudic, 1998). The LCA is separated physically from the UCA by the Eleana Formation and Chainman Shale (upper clastic confining unit). The Paleozoic carbonate rocks of the UCA and LCA are widely distributed in the eastern and southern parts of the DVRFS (fig. 3). These rocks are missing from the northwestern part of the study area because of thick accumulations of volcanic rocks and a facies change in Mississippian rocks from predominantly limestone and dolomite to predominantly argillite and quartzite.

Thirty-eight analyses of hydraulic properties were compiled for the upper and lower carbonate aquifers, 33 from single-well aquifer tests and 5 from multiple-well aquifer tests. Test-interval thicknesses ranged from 8 to 508 m. Aquifer-test pumping rates ranged from 0.9 to 7 L/s with a minimum pumping time of 180 minutes. To avoid biasing, aquifer-test analyses available for pumping wells were omitted from the statistical summaries when data or analyses for an observation well were available.

Horizontal hydraulic-conductivity values ranged from 0.00001 to 820 m/d with geometric and arithmetic means of 0.6 m/d and 90 m/d, respectively. The 95-percent confidence interval about the geometric mean for these values ranged from 0.2 to 2 m/d. Storativity values from 10 analyses of the pumping tests ranged from 0.0008 to 0.006 with an arithmetic mean of 0.003 (app. A).

The analyses were subdivided and statistically summarized to evaluate differences in hydraulic conductivity for rocks with extensive faulting with or without karst development, and rocks without extensive structural disturbance. The geometric mean of the horizontal hydraulic-conductivity values for extensively faulted and karstic limestone and dolomite was 3 m/d, whereas the geometric mean of hydraulic-conductivity values of unfaulted to simply faulted limestone and dolomite was 0.1 m/d. The difference between the geometric means of these two groups suggests that extensive faulting and karst development significantly increase hydraulic conductivity of the UCA and the LCA.

Upper Clastic Confining Unit and Lower Clastic Confining Unit

The upper clastic confining unit (UCCU) and the lower clastic confining unit (LCCU) consists of Late Proterozoic to Permian argillite, shale, siltstone, quartzite, sandstone, and conglomerate with subordinate chert, limestone, dolomite, and diabase. The UCCU and LCCU are regional confining units although the limestone, dolomite, and clastic rocks contained in them locally transmit water. Clastic rocks comprising the UCCU and the LCCU are widely exposed in mountainous areas bordering Yucca Flat, Pahrump Valley, and Death Valley (fig. 1). Upper Cambrian to Mississippian formations in this HGU intertongue with the LCA. The UCCU and the LCCU are considered as separate units in the DVRFS hydrogeologic framework but are combined in this report.

Twelve single-well analyses of hydraulic properties were compiled for the UCCU and the LCCU. Seventeen results of permeameter tests also were available. These permeameter tests were used to obtain estimates of matrix permeabilities of these confining units. Available analyses were from wells in and near the central and northeastern sections of the DVRFS. Test-interval thicknesses ranged from 15 to 1,285 m.

Horizontal hydraulic-conductivity values for the UCCU and the LCCU ranged from 0.00000003 to 5 m/d with geometric and arithmetic means of 0.00003 m/d and 0.2 m/d, respectively. The 95-percent confidence interval about the geometric mean for these values ranged from 0.000003 to 0.0003 m/d. The maximum hydraulic-conductivity value was obtained from an aquifer test in the Funeral Mountains (fig. 1) where the quartzites of the LCCU in this area possibly are sufficiently fractured to allow water to flow from Amargosa Desert into Death Valley (D'Agnese and others, 1997).

Because of different deformation behaviors, the UCCU and LCCU were subdivided for further statistical analyses. The UCCU is composed primarily of shale and the LCCU is composed primarily of quartzites. Shales tend to deform plastically, sealing fractures, while quartzites tend to be more brittle when deformed (Faunt, 1997).

Nine analyses of aquifer tests were available for the shale lithologies of the UCCU (Chainman Shale and the Eleana Formation). The geometric and arithmetic means of the horizontal hydraulic-conductivity values were 0.01 m/d and 0.07 m/d, respectively, with a range from 0.0003 to 0.4 m/d. The 95-percent confidence interval about the geometric mean for these values ranged from 0.002 m/d to 0.06 m/d.

Nineteen analyses of aquifer tests (field and laboratory) were available for the quartzitic lithologies of the LCCU. The geometric and arithmetic means of the hydraulic-conductivity values were 0.0000006 m/d and 5 m/d, respectively, with a range from 0.00000003 to 5 m/d. The 95-percent confidence interval about the geometric mean for these values ranged from 0.00000007 to 0.000005 m/d. However, using only the three pumping tests available for the quartzitic formations, a higher geometric mean hydraulic conductivity of 0.05 m/d is obtained with a range from 0.0002 to 5 m/d.

Crystalline Confining Unit

The crystalline confining unit (XCU) consists of Middle Proterozoic crystalline metamorphic and igneous rocks and metamorphosed Late Proterozoic sedimentary rocks. These granites and metamorphic rocks crop out mainly along the southwestern margins of the study area, in the Panamint Range and Black Mountains bordering Death Valley, and in the Nopah Range, Kingston Range, and Mesquite Mountains between Death Valley and Pahrump Valley (fig. 1; Grose and Smith, 1989). In most other areas, the crystalline confining unit forms the basement rock, which is generally deeply buried.

Although these rocks can produce small quantities of water through fractures and weathered zones, they are relatively impermeable and considered the base confining unit (Prudic and others, 1995; Bedinger and others, 1989). Bedinger and others report that rocks of this type, subdivided into weathered, shallow depth (less than 300 m), and deep depth (greater than 300 m) are characterized by hydraulic conductivities represented by geometric means of 0.03, 0.0005, and 0.0000003 m/d, respectively. The 85-percent confidence interval for weathered metamorphic rocks is 0.002 to 0.4 m/d; for shallow depth metamorphics is 0.00001 to 0.02 m/d; and for deep metamorphics is 0.00000002 to 0.000006 m/d (Bedinger and others, 1989).

RELATION OF HYDRAULIC CONDUCTIVITY WITH DEPTH

Researchers have estimated the depth of the flow system underlying the NTS area and postulated a somewhat qualitative relation between hydraulic conductivity and depth in the region. Winograd and Thordarson (1975) indicate that fractures in the carbonate aquifers are “open” (more permeable) to about 1,300 m below land surface and are “tighter” (less permeable) below this depth. D’Agnese and others (1997) indicate qualitatively that between depths of 300 to 1,000 m the hydraulic conductivity of most rocks in the DVRFS decreases rapidly. At depths greater than 1,000 m, matrix permeability probably dominates, except when within regional fault zones. Below 5,000 m, confining pressures likely keep faults and fractures closed (D’Agnese and others, 1997). The IT Corporation (1996b, p. 29) has postulated a relation of exponentially decreasing hydraulic conductivity with depth in the alluvial aquifer (equivalent to the YAA, OAA, and ACU), in the volcanic aquifer (equivalent to part of the Tertiary volcanics unit), and in the lower carbonate aquifer. While decreasing trends are apparent (IT Corporation, 1996b, figs. 6-1, 6-2, and 6-3), a great deal of scatter in the data also is apparent.

The relation of hydraulic conductivity and depth were examined for the 10 hydrogeologic units that overlie the XCU. Linear regression analysis showed the greatest correlation to depth occurred with the $\log_{10}$ transform of all hydraulic-conductivity estimates. The coefficient of determination (r^2) for the depth and non-transformed estimates is 0.003, while for the $\log_{10}$ transformed estimates it is 0.296. In contrast, the coefficient of determination of $\log_{10}$ transformed depth and non-transformed hydraulic-conductivity estimates was 0.245. The best relation, based on regression simulation, is the non-transformed depth with the transformed hydraulic-conductivity estimates and this model was used for the analyses of covariance (ANCOVA; see Neter and others (1985) for an explanation of analysis of covariance).

A plot of the $\log_{10}$ transform of hydraulic conductivity and the mid-point depth of the tested interval for the 10 HGUs are shown in figure 4. Visual examination

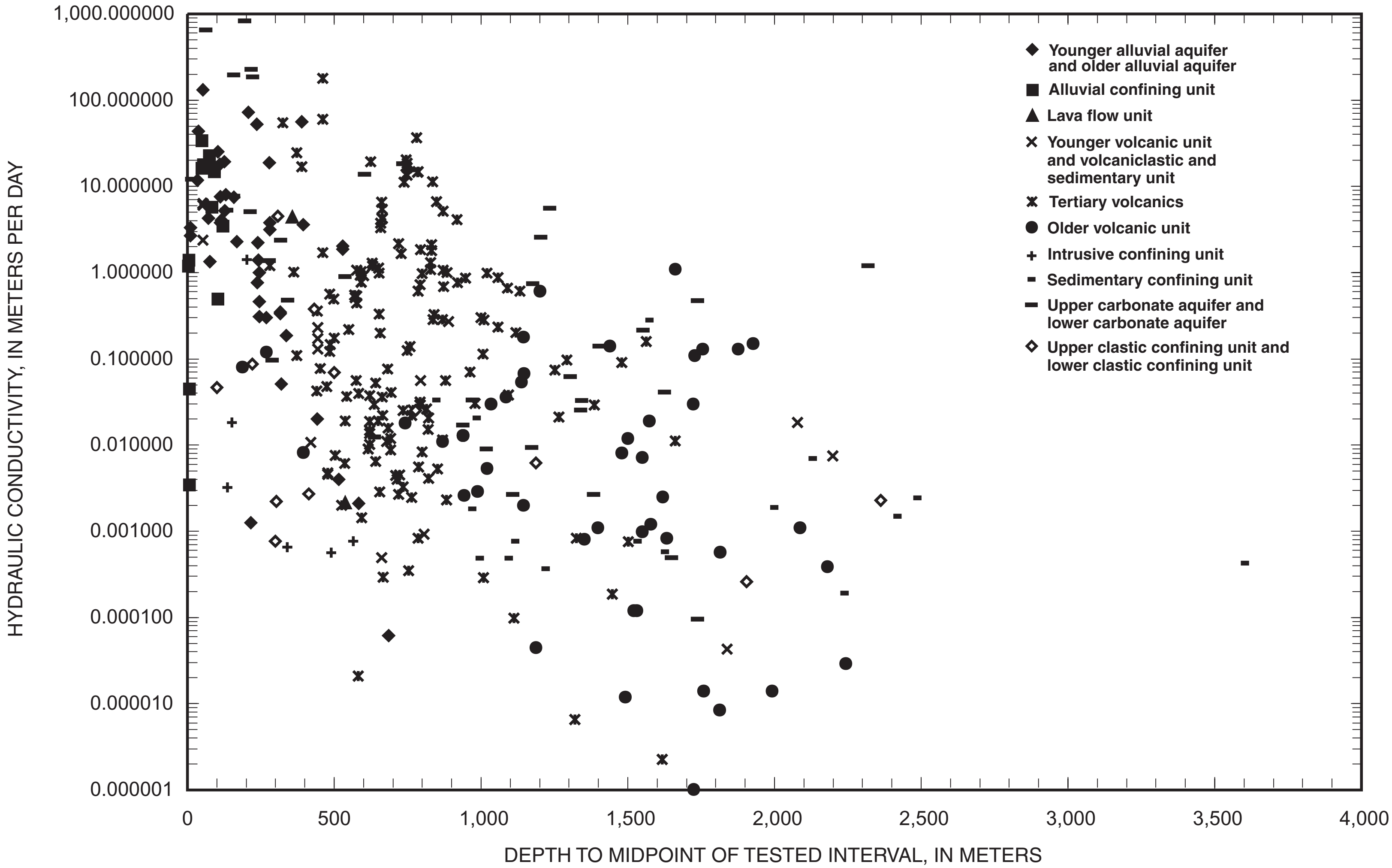

Figure 4. Relation between hydraulic conductivity and depth for hydrogeologic units in the Death Valley region.

Table 3. Analysis of variance for $\log_{10}$ hydraulic conductivity for estimates from aquifer tests as influenced by hydrogeologic unit and depth

[Abbreviation: HGU, hydrogeologic unit]

Source of variation	Degrees of freedom	Sum of squares	Mean square	F value [1]
Model (overall)	10	379.039	37.904	21.668
Error	339	593.295	1.750	
Total	349	972.334		
By model components				
Depth	1	288.286	288.286	164.722
HGU	9	90.753	10.084	5.762

[1] F value significant at probability level of 0.025.

of this plot shows an apparent relation between hydraulic conductivity and depth, but relatively high data scatter. ANCOVA initially were done on all hydraulic conductivity and depth data combined into a single data set to assess whether changes in hydraulic conductivity were related to HGU and depth. ANCOVA for the $\log_{10}$ transformed hydraulic conductivity estimates and depth for all HGUs indicate that depth and HGU are both significant factors at a probability level of 0.025 (table 3).

Since the HGU and depth were determined to be significant factors with the change of hydraulic-conductivity values, hydraulic-conductivity and depth data were categorized by an individual HGU and individually analyzed. Results from the ANCOVA for each individual HGU show a significant relation between depth and $\log_{10}$ transformed hydraulic conductivity at a probability level of 0.025 for five of the HGUs (YAA and OAA, YVU and VSU, Tertiary volcanics, OVU, and UCA and LCA. Although the ANCOVA of $\log_{10}$ transformed hydraulic-conductivity estimates indicate that depth may be a significant factor for the variation of hydraulic conductivity in five of the HGUs, the estimates can still vary considerably at a given depth. These large variations probably are caused by other factors (such as bedding, lithologic heterogeneities, or structural influences) that are not accounted for in these analyses. Additionally, some of the decrease in hydraulic conductivity with depth may be the result of using test-interval thickness for calculating hydraulic conductivity. That is, some of this decreasing trend in hydraulic conductivity possibly may be an artifact of the procedure used to calculate hydraulic conductivity from transmissivity.

SUMMARY AND CONCLUSIONS

The Death Valley region encompasses an area of about 43,500 km^2 in southeastern California and southern Nevada, between latitudes 35° and 38°15′ north and longitudes 115° and 117°45′ west. The study area is underlain by Quaternary to Tertiary basin fill sediments and mafic lava flows, Tertiary volcanic, volcaniclastic, and sedimentary rocks, Tertiary to Jurassic granitic rocks, Triassic to Middle Proterozoic carbonate and clastic sedimentary rocks, and Middle Proterozoic igneous and metamorphic rocks. As a result of several episodes of tectonic activity, rocks in the Death Valley region are faulted extensively. The hydraulic-properties database was compiled to support regional-scale ground-water flow modeling in the Death Valley region.

The DVRFS consists of interconnected hydrographic basins. Hydraulic connection between basins most commonly is maintained through unconsolidated sediments that were deposited across low topographic divides between the basins. Deep interbasin flow beneath valley floors and adjacent mountains and hills occurs primarily through fractured Paleozoic carbonate rocks.

Within the DVRFS, faults and related fractures are the largest influence on ground-water flow through bedrock aquifers. Faults disrupt stratigraphic continuity, which can divert water in regional circulation to subregional and local outlets. Less important than structure, but also an influence on ground-water flow is the lithology of rocks along flow paths.

Eleven HGUs were recognized in the DVRFS for the purpose of studying the distribution of hydraulic properties. Hydraulic properties were compiled and organized by these HGUs. Analyses also were performed to examine the relation between hydraulic conductivity and depth. Intuitively, hydraulic conductivity should decrease with depth as confining pressures seal fractures and faults and compress sedimentary units. ANCOVA indicate that depth is a significant factor in the variation of hydraulic conductivity, but the estimates can still vary a great deal at a given depth.

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APPENDIX

APPENDIX A: Hydraulic Properties Database

A hydraulic-properties database was compiled to support current Death Valley ground-water flow system simulations. The database contains individual worksheets for 10 of the 11 HGUs in the study area. No data were collected, and hence, no worksheet was required, for the Crystalline confining unit (XCU). Data reported in the body of the report for the XCU are from Bedinger and others (1989).

Entries for each HGU are organized by the well from which data were obtained (the observation well, if different from the pumping or injection well). Each entry in the database contains the following information:

1. Observation well name — A name commonly applied to the well from which hydraulic-property data were obtained.
2. USGS site identification (ID) number — A unique 15-digit number given to all inventoried wells in the USGS National Water Information System (NWIS) database. The site ID number consists of latitude, in degrees, minutes, and seconds, followed by longitude, in degrees, minutes, and seconds, followed by a sequence number. This field was left blank for wells that did not have a site ID number. Because data for wells in Permian sedimentary rocks from the Colorado Plateau that are in the database were obtained from a report in which these wells are identified by their land-net coordinates, a column containing land-net coordinates was added for these wells.
3. Universal Transverse Mercator (UTM) coordinates (meters). All well coordinates are in UTM zone 11, except those on the Colorado Plateau which are in UTM zone 12.
4. Land surface altitude at the well (meters). All altitudes are referenced to the National Geodetic Vertical Datum of 1929.
5. Well depth (meters).
6. Depths to the top and bottom of the test interval (meters).
7. Thickness (meters) — open interval of borehole.
8. Radius or interwell distance (meters) — for single-well aquifer tests, the borehole radius was listed if known; if the borehole radius was unknown, the casing radius was listed. For multiple-well aquifer tests, the reported, calculated, or scaled distance between the pumping or injection well and the observation well was listed.
9. Geologic units and lithologies present in the test interval — in test intervals spanning several geologic units, negligibly transmissive geologic units were omitted. For the Tertiary volcanics unit, columns describing alteration, degree of welding in ash-flow tuff, and the intensity of fracturing and faulting were added.
10. Pumped or injection well if different from the observation well (for HGUs with no multiple-well test data, this column was omitted).
11. Starting and ending test dates.
12. Length of the analyzed record, in minutes.
13. Type of aquifer test
14. Average discharge or injection rate (liters per second).
15. Analyzed data (typically drawdown, residual drawdown, recovery, specific capacity, or flux).
16. Hydraulic conductivity (meters per day) — Depending on available data, columns were added to list horizontal, vertical, fracture, and matrix hydraulic conductivity separately.
17. Vertical to horizontal anisotropy (for HGUs without data necessary to calculate this property, this column was omitted).
18. Transmissivity (meters squared per day).
19. Storativity (unitless).
20. Specific yield (unitless).
21. Analytical method, with analyses performed for this study identified.
22. Sources of hydraulic-property data, the aquifer-test analysis, and supporting data.